

# PULSED MICROWAVE SOURCE UTILIZING AN ALL SOLID STATE DRIVER FOR THE GENERATION OF TIME-MODULATED ECR PLASMAS\*

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## Abstract

An inexpensive pulsed microwave source has been developed for time-modulated electron cyclotron resonance (TMECR) plasma studies. Utilizing series IGBT switching, a high voltage modulator drives a standard 2M130 magnetron producing microwaves at 2.45 GHz. The microwave power waveform follows the TTL modulator trigger 2-500  $\mu$ s in width, at rep-rates up to 10 kHz and duty factors to 50%. Preliminary measurements of the TMECR plasma potential as a function of microwave pulsewidth, rep-rate, and duty factor are presented.

## I. INTRODUCTION

Conventional ECR plasma, inductively coupled plasma, and helicon wave plasma processes have a high etching rate but result in charge accumulation on substrates. TMECR plasma processing techniques modulate the plasma electron temperature using a pulsed discharge resulting in highly selective, high rate, notch-free, and charge-free etching [1],[2]. TMECR plasmas are produced using pulsed microwaves 10-100  $\mu$ s in pulse duration and spacing with duty factor ~50%. Typically, a highly stable, klystron-based source is used to generate the pulsed microwaves. However, these systems are costly. An inexpensive pulsed microwave source, based on a versatile solid-state modulator driving a conventional CW magnetron, was postulated. The modulator was designed, built, and tested at the Naval Research Laboratory. The design utilizes series IGBT switching modules and is presently capable of producing square pulses of up to 8 kV and 70 A. The pulse width is variable from 2-500  $\mu$ s with a maximum PRF of 10 kHz. A series of tests were conducted using an 850 W microwave-oven magnetron driven by the solid state modulator at 3-5 kV and ~1 A to produce pulsed microwaves at 2.45 GHz. The source was characterized using a dummy load and directional coupler to measure incident power as a function of driving pulse width. Magnetron cathode voltage and anode current were also measured. The waveform of the incident power followed

the TTL trigger signal exactly, indicating excellent pulsed operation. There was no indication of moding in the magnetron. The pulsed system was then adapted for use on an existing ECR experiment. A time-modulated ECR plasma was produced with the system in initial experiments using 25  $\mu$ s and 50  $\mu$ s pulses at 10 kHz rep-rate for a 25% and 50% duty factor. Emissive probe data indicate that the plasma potential is modulated with the input TTL trigger signal.

## II. SOLID STATE DRIVER

As an economical and reliable solution to the TMECR experimental requirements, a modulator based on series IGBT switching was designed, built and tested using a resistive load.

### A. Design

IGBTs were chosen to serve as the primary switching element in the modulator. In general, IGBTs have high current capability with low ohmic losses and can be gated at high frequency using a low voltage. Circuits with parallel IGBTs are relatively commonplace; however, at the time of the design, there were only a few publications addressing the series connection of these switches [3],[4],[5],[6]. The main design issues were circuit topology, voltage balance in steady state, gate drives, isolated power supply, snubbing, and cooling.

The circuit layout is shown in Fig. 1. An IXYS (type IXSK35N120AU1) IGBT with  $V_{CES}=1.2$  kV and  $I_C=35$  A @90° C was chosen to meet the modulator requirements. Each IGBT and its gate drive circuitry was mounted on a single board and the boards were stacked in series. The stack was mounted as a series switch that modulates a capacitive discharge. Individual boards simplify troubleshooting and repair. The basic circuit of the board follows the work outlined in reference 6, which has proven reliable. The modulator was originally designed for 8 kV – 8 series IGBT boards operating at 1 kV each. The switch stack was protected from short circuit loads by a 190  $\Omega$ , 300 W resistor network.

\* Work supported by the Office of Naval Research

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Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>JUN 1999</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Pulsed Microwave Source Utilizing An All Solid State Driver For The Generation Of Time-Modulated Ecr Plasmas</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Plasma Physics Division Naval Research Laboratory Washington, DC 20375</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>SAR</b>	18. NUMBER OF PAGES <b>4</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

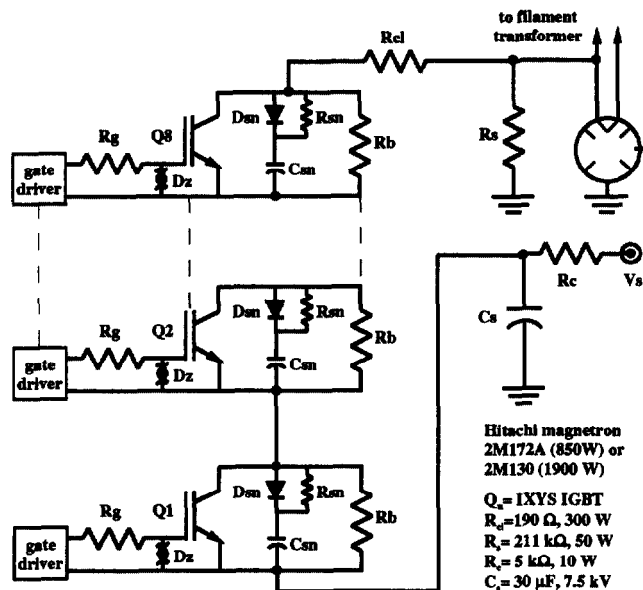


Figure1- Circuit layout of modulator.

In the steady state, the total voltage should be equally shared by each series stage in the switch stack. A simple resistor chain serves to achieve this balance. A design equation for a conservative value of the resistor that may be used in the network is given by  $R_b = (0.9nV_{CES} - V_o) / (\Delta I_{CES}(n-1))$  where  $n$  is the number of IGBTs in series and  $\Delta I_{CES}$  is the maximum difference in leakage current (which is temperature dependent) [3]. In this case, a network of 1.5 MΩ, 2W Allen-Bradley resistors was implemented.

The gating of each stage must be simultaneous to assure that the supply voltage is equally shared by the IGBTs during the switching transient. There are two basic approaches to gating a series connection of IGBTs: i) driving each IGBT in series with synchronized pulses or ii) equalizing switching times with an optimized driving circuit using capacitive coupling between output and driving circuits. The former can be accomplished with careful control of the driving and coupling circuits and was the method used in the modulator design. Fuji Electronics supplied the gate drivers (type EXB844) which are optimized for the IGBT and use optical isolation, greatly simplifying the driving circuit. The photo-coupler isolation withstood 10 kVDC for extended times during testing. Synchronization of the eight gate pulses within 15 ns was achieved by component matching. The gate driver also requires an isolated, 20 V, 100 mA power supply. The AAK Corporation supplied a chassis mount power supply model CM20.1-7. Voltage regulation was 0.05% and the transformer isolation was tested to 10 kVDC. A HP signal generator supplies square pulses of various widths and spacing, at different frequencies, to a TTL circuit with a fanout that feeds all the photo-couplers in the gate drives simultaneously to trigger the unit.

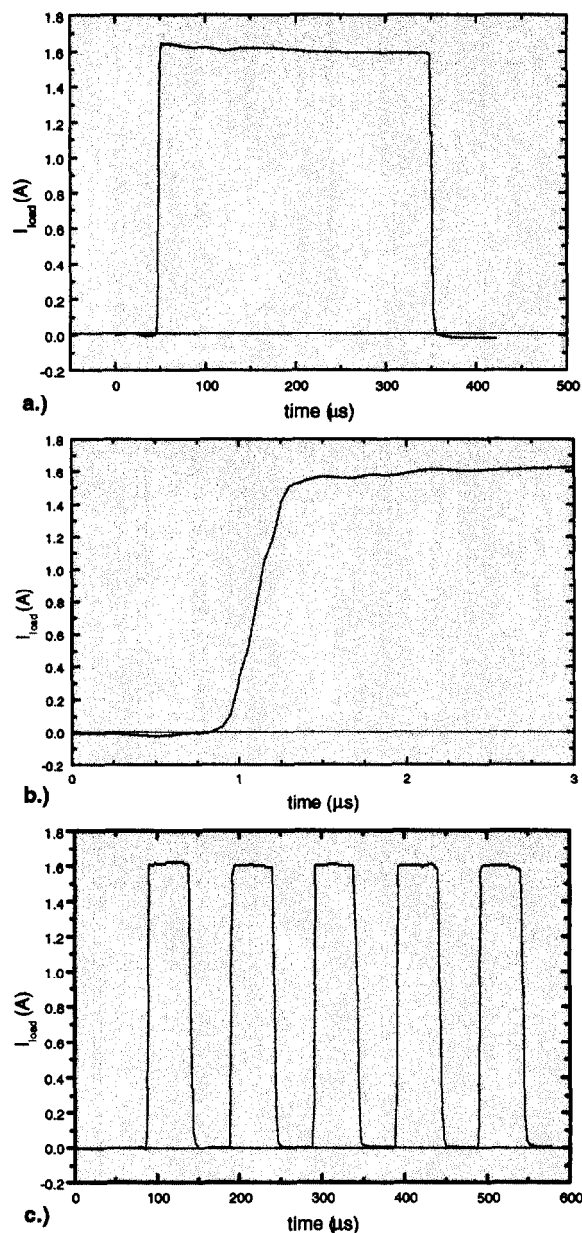


Figure 2- Testing using a resistive load: a) output current in response to a 300 μs TTL input trigger, b) risetime of a typical pulse, and c) operation at 10 kHz and 50% duty.

Energy stored in stray reactances in the circuit can pose a problem for the IGBTs especially during the turn-off portion of the switching transient. Typically, a snubber circuit is used to dissipate potentially destructive reactive energy and protect against over-voltage of the IGBT. The most practical snubber circuit for the application was a charge-discharge RCD circuit since the device would not be operated at very high frequencies and losses in the snubber resistance were unimportant. The snubber capacitance is given by  $C_{sn} = L_s \cdot I_o^2 / (V_{CES} - V_o)^2$  where  $L_s$  is the circuit stray inductance. The snubber

resistance is given by  $R_{sn} = (6 * C_{sn} * f_{sw})^{-1}$  where  $f_{sw}$  is the switching frequency [3].

Since operation at 50% duty factor was desired, significant energy would be dissipated in the series resistance in the circuit and in the IGBTs. Custom heat sinks were made for the IGBTs and the modulator was designed with forced-air cooling of the switches and resistors.

### B. Testing with resistive load

Results of the testing of the modulator are shown in Fig. 2. A 4 k $\Omega$ , 1 kW resistor network was used to simulate a magnetron load on the modulator. The 30  $\mu$ F capacitor was charged to 6.5 kV (about 800 V/stage) and initially, the TTL pulsewidth to the photo-couplers was set at 300  $\mu$ s. Fig. 2a shows the measured 1.6 A load current that nicely follows the input TTL trigger signal. The 10-90% risetime of this pulse, shown in Fig. 2b, is  $\sim$ 400 ns. Reproducibility was excellent. The TTL pulsewidth was then adjusted to 50  $\mu$ s and the frequency set at 10 kHz for a 50% duty factor. Fig. 2c shows the measured load current waveform which is well modulated by the input trigger signal. The modulator proved to be very consistent and reliable during the testing.

## III. PULSED MICROWAVE SOURCE

Given that a klystron-based, pulsed microwave source would be too costly, an inexpensive, magnetron-based alternative was sought. Standard, pulsed magnetrons used in radar applications usually require very high voltage modulators (>20 kV) which typically deliver short pulses at low duty factor. In general, they do not meet the TMECR experimental requirements. The question arises: can a standard CW magnetron, similar to the type used in microwave ovens, operate in a pulsed mode such that it can deliver a fast rising, flat-topped pulse of variable width? The main concerns with this scheme are moding in the magnetron and filament lifetime.

### A. Design and experiment

The goal is to demonstrate whether the microwave output power from a standard CW magnetron can follow the input TTL trigger pulse to the modulator without observing moding (or any other problems) in the magnetron. A 2M172A magnetron (2.45 GHz, 850 W) was appropriately mounted in a piece of WR-284 waveguide. A 60 dB directional coupler and a matched dummy load were then mounted to the waveguide for testing. The modulator was connected directly to the magnetron; a standard filament transformer was connected and set up to run continuously. Forced-air cooling of the magnetron was provided by a squirrel-cage fan. A high-voltage Tektronix probe (model P6015) measured the magnetron cathode voltage. The anode

current was measured with a Pearson 110A monitor. Magnetron output power was measured in the directional coupler using a HP-8474B crystal detector. The pulse width was varied from 2-500  $\mu$ s and the frequency varied from 1 Hz to 10 kHz resulting in duty factors of 10-50%.

### B. Test results with dummy load

The output power waveform, as measured by the HP-8474B crystal detector, followed the input TTL modulator trigger signal for single pulses 2-500  $\mu$ s in width. This result is illustrated in Fig. 3 for a 50  $\mu$ s pulse. The magnetron output power into the dummy load is  $\sim$ 800 W. Rep-rate capabilities were tested using a 50  $\mu$ s pulse at frequencies up to 10 kHz. While testing at 2 kHz problems were observed. During operation, various parasitic capacitances are charged which hold the voltage of the cathode high between pulses. This may affect IGBT switching. The stray capacitances were measured: the magnetron accounted for 0.66 nF, the filament transformer-0.12 nF, and the charging cable and leads-0.3 nF. A shunt resistance was added to the circuit and the RC discharge time adjusted until the modulator switching was unaffected at 10 kHz. The final value of the shunt resistance was 200 k $\Omega$ , 50 W. Thereafter, the magnetron output power followed the input trigger signal to the modulator exactly. The pulsed microwave source with the dummy load tested reliably at 10 kHz, 50% duty for 2 hours. There was no evidence of moding in the magnetron.

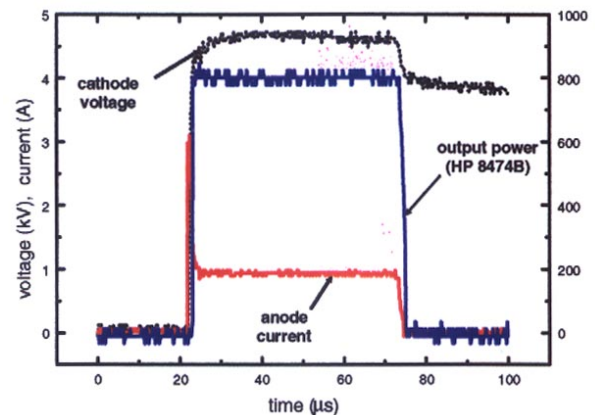


Figure 3- Test results of pulsed microwave source with a dummy load.

### C. TMECR plasma production

For the plasma production experiments, the modulator was connected directly to the 2M130 magnetron (1.9 kW, 2.45 GHz) of an existing ECR system. The magnetron feeds through a circulator, directional coupler, and stub tuning system to the magnetic field region of a vacuum chamber. The magnetic field configuration that was used placed the ECR resonance zone approximately 10 cm from the input vacuum window, with the field falling off

downstream. Initial experiments were performed under standard ECR conditions of 1 mTorr argon at 10 sccm flow. The system was tuned to minimize reflected power at each input power level and duty factor that was tested. Forward and reflected microwave power, and the plasma potential was measured as a function of pulse width, frequency, and duty factor. The plasma potential was estimated based on comparisons of I-V curves obtained using a heated Langmuir probe under non-emitting and emitting conditions. In general, the reflected microwave power was greater for shorter pulses and lower duty factor. Higher power (a factor of 2.5) was needed at 25% duty factor in order to get the same absorbed energy as in the 50% duty case. Fig. 4 shows the Langmuir probe measurements. The plasma potential/plasma electron temperature follows the input microwave power closely. Separate measurements taken with the probe biased strongly negative (to collect ion saturation current) indicate that the plasma density shows much less modulation. These results agree with other TMECR experimental findings [7]. The actual modulation in plasma potential is probably sharper than shown because of inadequate bandwidth of the isolator used with the Langmuir probe. The pulsed microwave plasma source operated consistently and reliably for up to 5 hours per day at 50% duty.

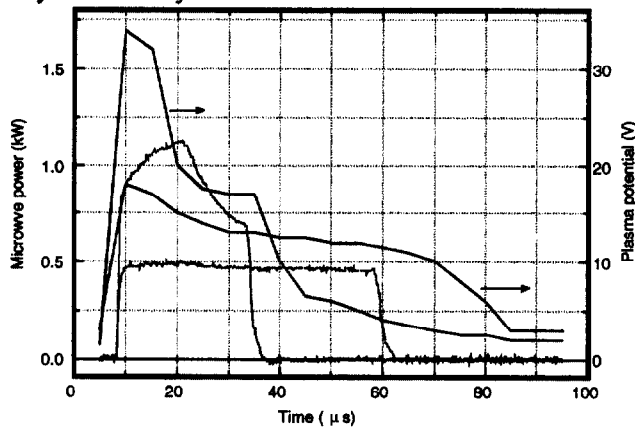


Figure 4- Emissive probe data for TMECR operation at 10 kHz, 25% and 50% duty. The dashed curves are incident microwave power; the solid curves are plasma potential.

#### IV. CONCLUSIONS

An all solid state modulator capable of 2-500  $\mu$ s pulses, rep-rates up to 10 kHz, and duty factor up to 50% was designed, built and tested. The modulator was successfully coupled with a standard CW magnetron to create an inexpensive pulsed microwave source. The microwave output power follows the input TTL trigger signal to the modulator at 10 kHz and 50% duty with no evidence of moding in the magnetron. After several months of continuous operation, filament lifetime has not become an issue. The microwave source was implemented on an existing ECR set-up and the system

was tuned to produce a consistent time-modulated ECR plasma for plasma processing experiments. Preliminary measurements indicate that the plasma potential/plasma electron temperature is modulated with the input microwave power and that the plasma density shows much less modulation. These measurements are consistent with other published work indicating that the time-modulated ECR plasma is suitable for further plasma processing experiments.

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